Agricultural Water Management 97 (2010) 1787–1794

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

# Infrared canopy temperature of early-ripening peach trees under postharvest deficit irrigation

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ARTICLE INFO

*Article history:*
Received 29 July 2009
Accepted 22 June 2010
Available online 21 July 2010

*Keywords:*
IRT
CWSI
Stem water potential
Peach yield
Fruit quality

ABSTRACT

Canopy temperature measurements with infrared thermometry have been extensively studied as a means of assessing plant water status for field and row crops but not for fruit trees such as peaches. Like in many regions of the world, the lack of water is beginning to impact production of tree fruit such as peaches in the San Joaquin Valley of California. This is an area where irrigation is the only source of water for agricultural crops in the summer growing season. A two-year field study was conducted to assess plant water stress using infrared canopy temperature measurements and to examine its feasibility for managing postharvest deficit irrigation of peach trees. Twelve infrared temperature sensors were installed in a mature peach orchard which received four irrigation treatments: furrow and subsurface drip irrigation with or without postharvest water stress. During the two-year period, measured midday canopy to air temperature differences in the water-stressed postharvest deficit irrigation treatments were in the 5–7 °C range, which were consistently higher than the 1.4–2 °C range found in the non-water-stressed control treatments. A reasonable correlation ($R^2$ = 0.67–0.70) was obtained between stem water potential and the canopy to air temperature difference, indicating the possibility of using the canopy temperature to trigger irrigation events. Crop water stress index (CWSI) was estimated and consistently higher CWSI values were found in the deficit irrigation than in the control treatments. Results of yield and fruit quality assessments were consistent with the literature when deficit irrigation was deployed.

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## 1. Introduction

California has been under an extended drought due partly to below average precipitation, partly to early Sierra Nevada snowmelt (higher night-time temperatures as a result of global climate change) that reduces water availability during the summer growing season (CDWR, 2009). Approximately 10,000 ha of commercially grown peach trees in central California depend on this water as the primary source of water supply. Although well water is available, the lack of surface water resulting in the increased pumping from groundwater has resulted in a declining water table (Faunt et al., 2009). For existing peach trees, a potential solution for water shortage is to adopt deficit irrigation strategies or regulated deficit irrigation (Girona et al., 2005).

Regulated deficit irrigation has been studied for many tree crops and vines as a means of reducing total water use (Goldhamer et al., 2006; Fereres and Soriano, 2007; Testi et al., 2008) and in some instances for manipulating crop quality such as in wine grapes (Williams et al., 1994; Bravdo and Naor, 1996). Deficit irrigation has been an interest for many fruit trees because fruit yield and quality at harvest are not sensitive to water stress at some developmental stages (Johnson and Handley, 2000). According to Chalmers et al. (1981), a reasonable plant water stress in fruit trees can improve the partitioning of carbohydrate to reproductive parts such as fruit and at the same time provide a control on excessive canopy growth. A recent study indicated that deficit irrigation could also be used in certain stages of corn growth to facilitate translocation of carbohydrate into grain and cob rather than into stover (Payero et al., 2009).

When crops are managed under deficit irrigation, the margin of error in timing and amount of water application becomes smaller before causing yield losses (Goldhamer et al., 1999). Monitoring the soil and plant water status is more critical for reducing risks of causing a crop failure or permanent damage to the trees. However, current established techniques of monitoring the soil and plant water status such as neutron probe readings of soil water profile, stem water potential measurements, or trunk diameter shrinkage measurements are quite labor intensive, often lacking the timeliness needed for day-to-day irrigation decisions. There is a general lack of adoption of deficit irrigation due partially to the lack of effective and fast methods for guiding the management and the associated risks of applying deficit irrigation.

Infrared thermometry or thermal imaging could be a useful technique for monitoring stomatal conductance in fruit trees and vines at high temporal frequencies (Jones, 1999, 2004). Based on

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0378-3774/$ – see front matter Published by Elsevier B.V.
doi:10.1016/j.agwat.2010.06.014

canopy temperature measurements of peach trees using infrared thermometers, Glenn et al. (1989) showed that canopy and air temperature difference was related to the air vapor pressure deficit, a parameter also reflected in stomatal responses to water stress. Water stress in wine grapes in northern Israel was more precisely estimated using the crop water stress index (CWSI) when both thermal and visible images were used (Moller et al., 2007). Infrared thermal imagery was also found effective in timely determination of plant water stress in apple and peach orchards (Giuliani et al., 2001), olive orchards (Sepulcre-Canto et al., 2006), or pistachios (Testi et al., 2008). For field crops, Sadler et al. (2002) deployed an array of 26 infrared temperature sensors on a center pivot irrigation system for monitoring irrigation uniformity. Based on infrared canopy temperature measurements and principles of canopy energy balance, Wanjura and Upchurch (1997) developed a temperature time-threshold model and demonstrated applications in irrigation scheduling in cotton. In other studies such as that of Massai et al. (2000), application of leaf temperature on describing fruit tree water status was found to be prone to high variability. There is no information available in the literature on applying an infrared canopy temperature-based approach for managing deficit irrigation in Prunus crops such as peaches. To help ameliorate water shortage in California and other parts of the world, an approach such as the temperature time-threshold method should be explored. The objective of this study was to evaluate characteristics of canopy temperature of early-ripening peach trees with respect to soil water content and stem water potential measurements under different irrigation regimes, including postharvest regulated deficit irrigation. The final goal was to develop a canopy temperature-based irrigation scheduling mechanism for managing deficit irrigation in peaches.

## 2. Materials and methods

### 2.1. Orchard and experiment description

The study was conducted in a 1.6 ha peach orchard at the USDA-ARS San Joaquin Valley Agricultural Sciences Center located near Parlier, CA (36°37′N; 119°31′W). The soil at the study site is a Hanford sandy loam soil (coarse-loamy, mixed, thermic Typic Xerorthents). A detailed description of the orchard can be found in Bryla et al. (2005). Briefly, early-ripening “Crimson Lady” (*Prunus persica* (L.) Batsch) peach trees on “Nemaguard” rootstock were planted in April 1999. The trees were spaced 1.8 m apart within rows and 4.9 m between rows.

The experimental design was a randomized block with furrow and subsurface drip irrigation treatments as the main effect and levels of postharvest deficit irrigation the sub-effect. The experimental treatments were designated as:

(1) F1 representing furrow irrigation to replace 100% crop evapotranspiration (ETc) based on a crop water use curve developed from recent weighing lysimeter measurements in a nearby peach orchard,
(2) F2, furrow irrigation to replace 100% ETc before harvest, and postharvest deficit irrigation initiated when stem water potential approached −2 MPa,
(3) S1, subsurface drip irrigation to replace 100% ETc as for F1,
(4) S2, subsurface drip irrigation to replace 100% ETc before harvest, and postharvest deficit irrigation to replace only 25% ETc.

A total of six replications were used, with each replication including the four irrigation treatments or a total of 24 treatment plots for the study. Each treatment plot consisted of three rows with eight trees per row. The middle six trees in the center row were used for all the soil water content and plant-based measurements, including yield and fruit quality assessments. The irrigation treatments were initiated in 2005 after peach harvest, however, actual data collection was made for the 2007–2008 and 2008–2009 seasons to acclimate the trees to the irrigation treatments from the previous full irrigation studies.

### 2.2. Operation of infrared temperature sensors and calculation for CWSI

Twelve infrared temperature sensors (Apogee Instruments, Inc., Logan, UT) were installed in three of the six replicated plots within the peach orchard to measure canopy temperatures. The sensors were installed in the field on 5–6 July 2007 by mounting them on 5-cm diameter galvanized metal pipes 5.5 m above the soil surface. All sensors were pointed southward at approximately 30° from nadir with the center of field of view (FOV) aimed at the middle three trees of the center row. The aiming was achieved by mounting a webcam camera in parallel with the infrared sensors and a picture was also recorded for each location during the installation. Because of non-uniform tree growth, realignment of the sensors was made on 11 August 2007 by accessing the sensors with a mechanical lift and temporarily placing the webcam against the sensors. An automated datalogger system was employed to record temperature readings at 5–15 min intervals from the 12 infrared temperature sensors. The system consisted of three clusters, with each cluster representing one replication of the four irrigation treatments, e.g., F1, F2, S1, and S2. One CR10X datalogger (Campbell Scientific, Inc., Logan, UT) was used for each cluster to record infrared temperature readings from each treatment. A MD9 multi-drop network system (Campbell Scientific, Inc., Logan, UT) was also used to connect the three clusters/dataloggers through a coax cable and the data were retrieved at a central station located outside the orchard.

Because of differential distances from the location of the CR10X datalogger and the four infrared temperature sensors within each cluster, different lengths of extension (24.4–48.8 m) were added to each sensor in order for connecting them to the same datalogger. To correct for potential signal loss in the extension, laboratory calibrations were made, before their field installation, using a constant temperature water bath at multiple temperature settings. A new calibration was created for each sensor.

Rather than the absolute canopy temperatures, the difference between canopy and air temperature ($\Delta T = T_{\text{canopy}} - T_{\text{air}}$) was computed for each day to best describe plant water status because a significant increase in $\Delta T$ would indicate stomatal closure hence water-stressed conditions (Jackson et al., 1981). Air temperature and other meteorological parameters were obtained from a nearby weather station (California Irrigation Management Information Systems or CIMIS, California Department of Water Resources, Sacramento, CA). The crop water stress index (CWSI) was also computed using the energy balance method of Jackson (1982):

$$\text{CWSI} = 1 - \frac{E}{E_p} = \frac{\gamma(1+(r_c/r_a)) - \gamma^*}{\Delta + \gamma(1+(r_c/r_a))} \tag{1}$$

$$\frac{r_c}{r_a} = \frac{\gamma r_a (R_n/(\rho c_p)) - (T_c - T_a)(\Delta + \gamma) - \text{VPD}}{\gamma[(T_c - T_a) - r_a(R_n/(\rho c_p))]} \tag{2}$$

$$r_a = \frac{4.72[\text{Ln}((z-d)/z_o)]^2}{1 + 0.54u} \tag{3}$$

$$\Delta = \frac{bce_s(\bar{T})}{(c+\bar{T})^2} \tag{4}$$

where $E$ and $E_p$ are actual and potential evapotranspiration, respectively. $\gamma$ is psychrometric constant (0.0652 kPa °C$^{-1}$) and $\gamma^*$ is apparent psychrometric constant estimated from $\gamma$ $(1+u/3)$, in which $u$ is wind speed (Allen et al., 1994). $r_c$ and $r_a$ are canopy and aerodynamic resistance, respectively. $\Delta$ is the saturation vapor pressure function (Campbell and Norman, 1998) in which $b = 17.502$, $c = 240.97$ (°C), $e_s$ = saturation vapor pressure at $\bar{T} = (T_c + T_a)/2$, and $T_c$ and $T_a$ are canopy and air temperature, respectively. $R_n$ is net radiation and $\rho c_p$ is density and specific heat of air. VPD is vapor pressure deficit. $z$, $d$, and $z_o$ are, respectively, sensor height (2 m above canopy), displacement height (=0.6 h), and the roughness parameter (=0.015 h) where $h$ is canopy height (=3.6 m for the peach orchard).

### 2.3. Plant and soil water status measurements

To closely monitor plant and soil water status, stem water potential and soil water content were measured approximately weekly after peach harvest at the end of May and continued for the rest of the year for the 2007–2008 and 2008–2009 growing seasons. Stem water potential was measured using a pressure chamber (model 3000-1412, Soil Moisture Equipment Corp., Santa Barbara, CA) between 1300 and 1500 h pacific daylight savings time. Prior to each measurement, shaded leaves were covered in aluminum foil bags for 2 h before cutting then measured in the pressure chamber. The stem water potential measurements were used not only as an indicator for plant water status assessment but also as a guide for scheduling irrigations for the F2 treatment. Soil water content was measured weekly using a calibrated neutron probe (Series 4300, Troxler International, LTD., Research Triangle Park, NC) with galvanized steel access tubes located at the middle of the center row within each treatment plot. To provide an assessment on soil water status for the root zone profile, readings were made at 15, 45, 75, 105, 135 cm depths.

In addition to stem water potential and soil water content, peach fruit yield was measured for both the 2007–2008 and the 2008–2009 seasons and fruit quality was assessed for the 2007–2008 harvest. Marketable-sized fruits were picked by a commercial harvesting crew (Sunny Cal, Reedley, CA) following typical farming procedures. A total of three picks, about three days apart, were used during each season. For the experimental plots, the total number of peaches per tree and weight per tree were measured for each treatment plot. Average weight per fruit was calculated by dividing the weight per tree with number peaches per tree. For the 2007–2008 harvest, fruit quality was assessed by randomly selecting 100 peaches per plot (or a total of 600 peaches per irrigation treatment) and counting the number of peaches with doubles, deep sutures, external splits, dimples, deformations, or internal split pits. The remaining peaches (without any aforementioned deformities) were considered marketable.

### 2.4. Statistical analysis

Fruit yield and quality were analyzed with analysis of variance using Proc glm procedures (SAS Institute, 2003). Means were separated at $P = 0.05$ level using the Tukey's studentized range (HSD) test.

## 3. Results and discussion

### 3.1. Canopy temperature and CWSI characteristics

An example was provided for laboratory calibration one (sensor # 1351) of the 12 infrared temperature sensors for correction of variable lengths in sensor leads (Fig. 1). Using the new linear regression equation derived from a water bath under five temperature settings, final temperature variations in sensor readings were within 0.1 °C. The same thermal or long-wave emissivity was assumed for the water surface (0.96) and the peach tree canopy (0.94–0.99) (Campbell and Norman, 1998).

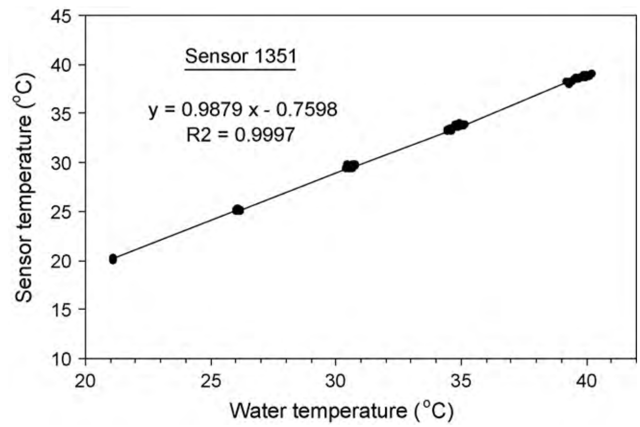


**Fig. 1.** An example of laboratory calibration of infrared temperature sensors using a water bath under five temperature settings for correction of variable lengths in sensor leads. The same thermal or long-wave emissivity was assumed for the water surface and the peach tree canopy.

Canopy temperature measurements can be affected by not only the solar but also the view zenith and azimuth angles. The interrelations between solar and view angles are complex. To help illustrate the relationships, solar zenith and azimuth for Parlier, CA were computed using following equations (Campbell and Norman, 1998):

$$\psi = \cos^{-1}\{\sin\phi\sin\delta + \cos\phi\cos\delta\cos[15(t - t_o)]\} \quad (5)$$

$$\alpha = \cos^{-1}\left[\frac{\cos\ \psi\sin\phi - \sin\delta}{\cos\phi\sin\psi}\right] \quad (6)$$

where $\phi$ is the latitude, $\delta$ is solar declination, $t$ is time, and $t_o$ is the time of solar noon.

In general, a small view zenith (nadir or close to nadir) would enable the sensor to see leaves deeper in the canopy and higher probability of seeing bare soil than a larger view zenith. View azimuth, when view zenith >0, may or may not have a big effect on the canopy temperature readings. As shown in Fig. 2a, solar azimuth at 1400 h decreases from approximately 70° in June–July to 40–50° in August–September. This means that when sensors are oriented south (0 azimuth), the angle between the sensor view and the solar azimuth at 1400 h would be approximately 70° in June–July to 40–50° in August–September rather than 180°. A right (90°) view azimuth to the sun was suggested by Huband and Monteith (1986) as a possible means of standardizing reading procedures. However, as can be seen from Fig. 2b, the solar azimuth also changes drastically on a diurnal cycle. So an option would be to mount the sensors facing east or west (or 90° view azimuth) then using the readings only at solar noon (0° solar azimuth). Similar to what was used in this study, the infrared sensor was mounted facing south with a view zenith of 30° for canopy temperature measurement of a lettuce crop (Alves and Pereira, 2000). Furthermore, the canopy to air temperature difference was found not significantly different when the canopy temperature was measured either from the top of a peach canopy or vertically from the side of peach trees (Glenn et al., 1989).

The diurnal canopy to air temperature difference or $\Delta T$ showed that, among the four irrigation treatments, the largest difference was in the deficit irrigation treatments, e.g., F2 and S2 (Fig. 3a). The daily peak values appeared to occur at approximately 1400 h pacific daylight savings time which was just after maximum daily solar radiation but before air temperature reached the daily maximum (Fig. 3b). The maximum $\Delta T$ values occurring at 1400 h were also reported by Massai et al. (2000). For the non-stressed irrigation treatment, e.g., F1 and S1, the peak $\Delta T$ values occurred around

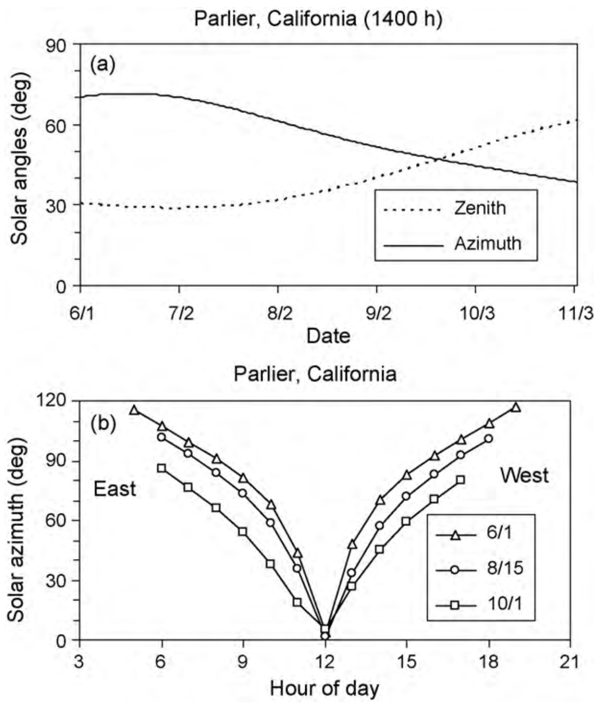


**Fig. 2.** Daily solar zenith and azimuth angles computed for 1400 h during June–October (a) and hourly solar azimuth angles on 6/1, 8/15, and 10/1 when solar zenith ≤90° (b) for Parlier, California (36°37′N; 119°31′W).

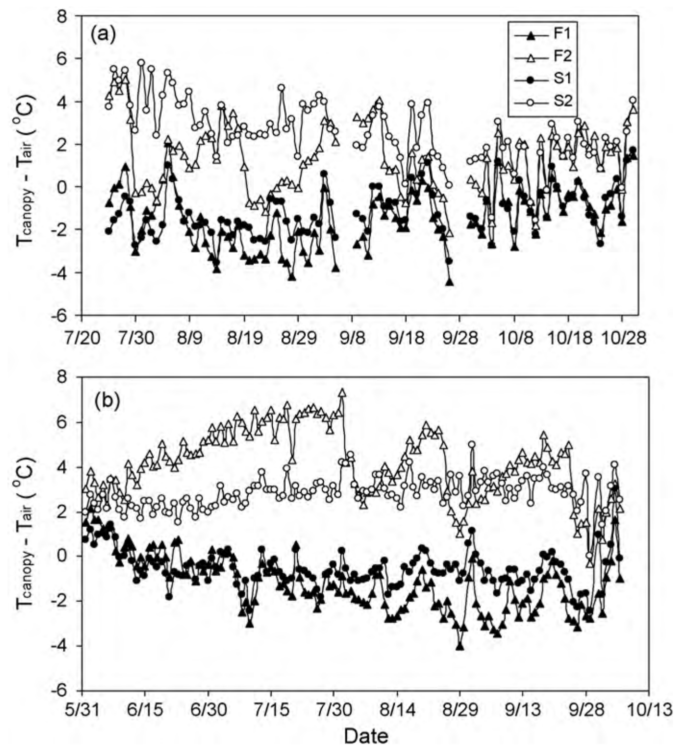


**Fig. 4.** Instantaneous canopy and air temperature difference at 2:00 pm pacific daylight saving time in (a) 2007 and (b) 2008. Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.

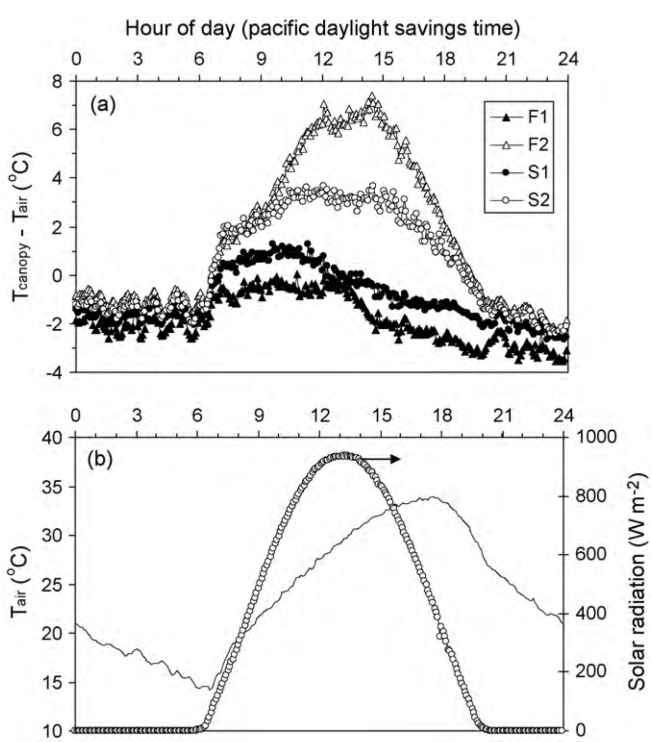


**Fig. 3.** Diurnal behavior of (a) canopy and air temperature difference, and (b) air temperature and solar radiation on 30 July 2008 at Parlier, CA. Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.

1000 h. There was virtually no difference in $\Delta T$ values between the irrigation treatments from approximately 2000 to 600 h the next morning when there was no solar heating.

Because diurnal $\Delta T$ patterns similar to that in Fig. 3a, responding to air temperature and radiative effect shown in Fig. 3b, were consistently observed for different days during the experiment, only the 1400 h (or 2:00 pm) $\Delta T$ values were presented for the 2007 and 2008 postharvest seasons (Fig. 4). Deficit irrigation treatments in F2 and S2 clearly showed higher $\Delta T$ values than the 100% ETc or F1 and S1 treatments throughout the postharvest period for both 2007 and 2008. The maximum $\Delta T$ values for F2 and S2 were 5.0 and 5.8 °C in 2007 (Fig. 4a); and 7.3 and 5.0 °C in 2008 (Fig. 4b), respectively. These maximum $\Delta T$ values were similar to the 5–6 °C range measured by Massai et al. (2000) in peach orchards located in Italy, Spain, and Portugal under non-irrigated water-stressed conditions. The maximum $\Delta T$ values for F1 and S1 were 2.1 and 1.7 °C in 2007; and 2.1 and 1.4 °C before 5 October 2008, respectively. The minimum $\Delta T$ values for F1 and S1 were −4.4 and −3.6 °C in 2007; and −4.0 and −2.5 °C in 2008, respectively. Large $\Delta T$ variations, especially in the F2 treatment, were attributed to irrigation events where a rapid drop in $\Delta T$ was related to irrigation. Differences in $\Delta T$ between the irrigation treatments started to disappear after the end of September when ETc reduced to approximately one-half of the peak values found in early July.

Seasonal patterns of CWSI (Fig. 5) showed a trend similar to the canopy temperature readings. The deficit irrigation treatments (F2, S5) clearly produced higher CWSI values than the non-water-stressed controls (F1, S2) in both growing seasons. In 2007, the estimated CWSI in F1 and S2 exhibited some level of water stress with CWSI values reached approximately 0.3 until large irrigation events reduced the index to near zero (Fig. 5a). A somewhat constant stress (0.4–0.5) was maintained in S5 during 25 July–1 September 2007, whereas the stress index showed large varia-

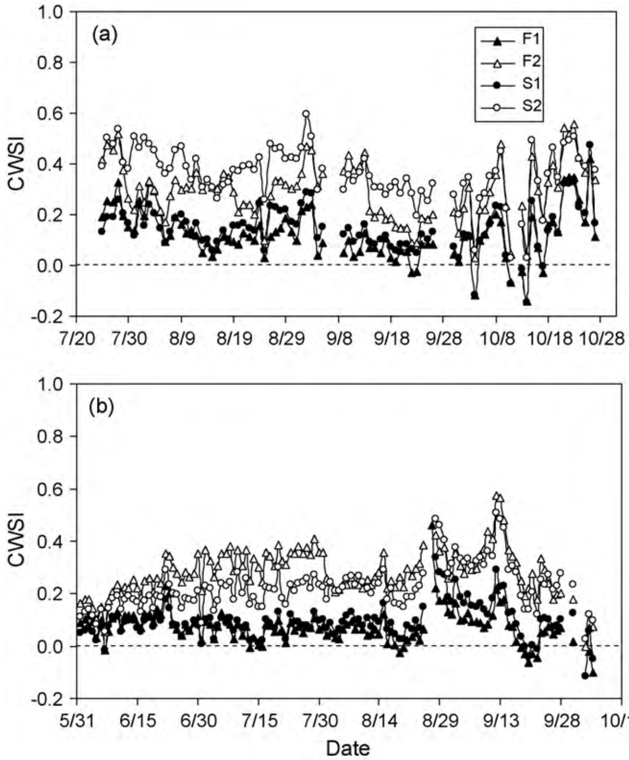


**Fig. 5.** Crop water stress index (CWSI) at 2:00 pm pacific daylight saving time in (a) 2007 and (b) 2008. Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.

tions (0.1–0.5) in F2 for the same time period, likely a result of less frequent irrigation events in the furrow treatment. In 2008, CWSI in the control treatments was maintained ≤0.1 and that in the deficit treatments was approximately 0.2–0.4 for June–August 2008 (Fig. 5b).

### 3.2. Stem water potential and soil water content

In 2007, stem water potential values were maintained in a relatively narrow range falling between −0.7 and −1.0 MPa in the fully irrigated F1 and S1 treatments (Fig. 6a). Whereas the stem water potential fluctuated drastically from approximately −1.0 to −1.9 MPa responding to each irrigation event in the F2 treatment, the value averaged about −1.5 MPa in the S2 treatment before 18 September 2007. Similar trends were observed in 2008, except the maximum stem water potential in the F2 treatment slightly exceeded −2.0 MPa (Fig. 6b). The deficit irrigation treatment, as shown in the F2 and S2 treatments, significantly increased plant water stress as quantified in stem water potential readings.

The weekly stem water potential measurements correlated reasonably well with the independent infrared canopy temperature to air temperature difference or $\Delta T$ measurements for both 2007 and 2008 (Fig. 7). The data set used in the figures included both full irrigation (F1 and S1) and deficit irrigation treatments (F2 and S2) covering a $\Delta T$ range of −4.0 to 7.3 °C. As shown in the figures, the coefficient of determination ($R^2$) was 0.67 and 0.70 for 2007 and 2008, respectively. Also a statistical analysis ($t$-test) showed that differences in slope and intercept between the 2007 and the 2008 linear regressions were not significant at $P = 0.05$. Although the simple empirical linear relationship is likely location (San Joaquin Valley of California) and plant (peach) specific, the correlation appears to be robust enough that it may be used as a guide

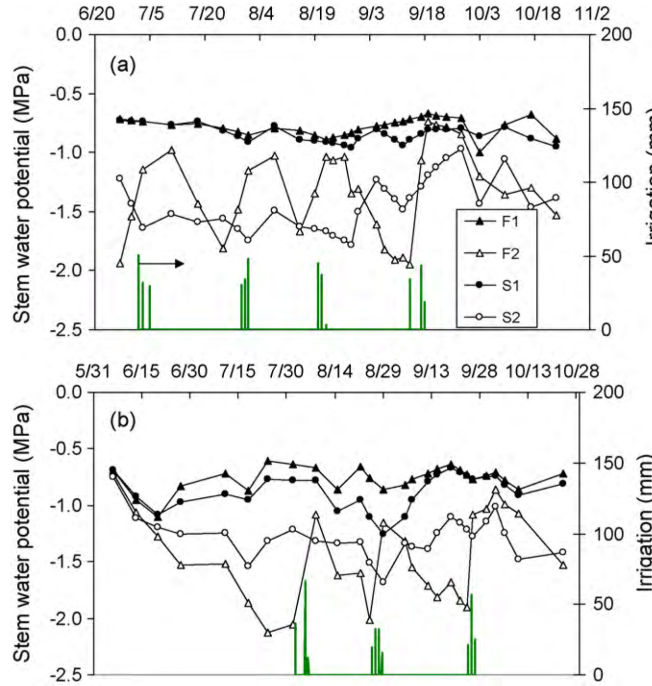


**Fig. 6.** Stem water potential and its responses to irrigation treatment in (a) 2007 and (b) 2008. Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc. Only F2 irrigation was shown because of lowest frequency and largest response in stem water potential.

for triggering irrigations. For example, if −1.5 MPa is the threshold stem water potential for initiating a deficit irrigation, rather than relying on manual pressure chamber measurements, the irrigation can be triggered when $\Delta T$ exceeds 2.75 °C (or stem water potential ≤−1.5 MPa). If the goal is to maintain the peach orchard for no water stress, then a target maximum $\Delta T$ of 1.25 °C (or ≥−1.3 MPa) may be used. The actual amount of irrigation to put on requires additional development. One approach is to adopt a method similar to that

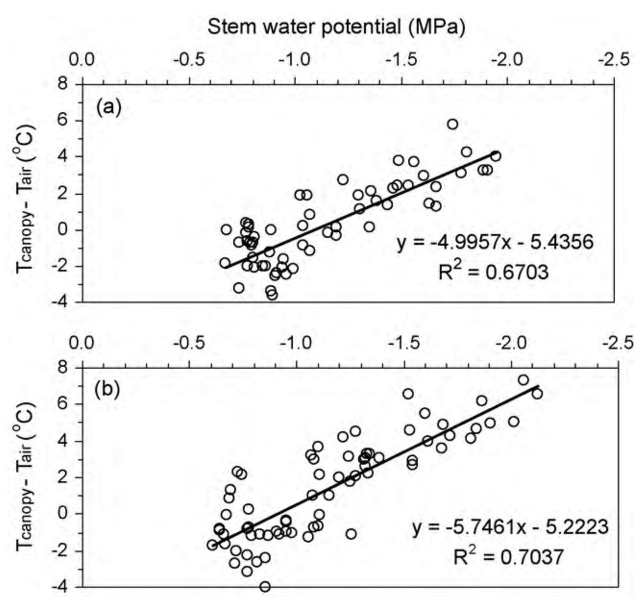


**Fig. 7.** Correlation of canopy and air temperature difference with stem water potential measurements from the (a) 2007–2008 and (b) 2008–2009 growing seasons at Parlier, CA.

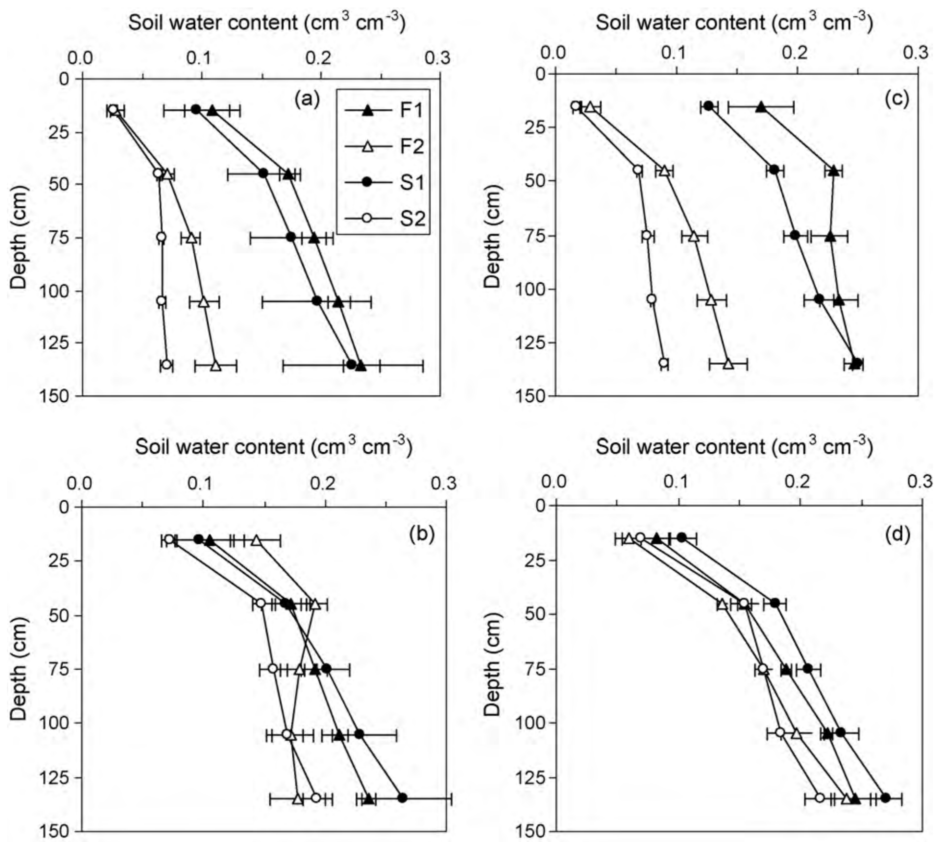


**Fig. 8.** Soil water content measured one day prior to an irrigation event on (a) 24 October 2007, (b) 6 Jun 2008, (c) 24 October 2008, and (d) 29 May 2009. During the 2007–2008 season, sub-figure (a) was measured at the end of non-fruiting bearing deficit irrigation period, and (b) was at the end of fruit bearing non-deficit irrigation period. Similarly during the 2008–2009 season, (c) was measured at the end of non-fruiting bearing deficit irrigation period, and (d) was at the end of fruit bearing non-deficit irrigation period. Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc. Bars are standard errors ($n$ = 3).

of Wanjura and Upchurch (1997) using the cumulative time above threshold $\Delta T$ and translating it to depth of water needed.

Compared to the 100% ETc irrigation treatments, e.g., F1 and S1, the effect of deficit irrigation treatments (F2 and S2) was also clearly reflected in a reduction of overall water content in the soil profile by the end of each growing season (Fig. 8a and c). The cumulative amount of water applied between June and November was 2.5–3.0 times lower in the F2 than in the F1 treatment and 3.4–4.0 times lower in the S2 than in the S1 treatment (Table 1). There was no significant difference in soil water content among treatments (F1, F2, S1, and S2) at the end of the non-water-stressed fruit bearing period (end of May to early June) (Fig. 8b and d). This result was expected because similar amount of irrigation water had been applied up to that time for each growing season (Table 1). If the level of water deficit was agronomically and economically acceptable, approximately 680 mm water could be saved using a postharvest deficit irrigation scheme by applying only an average of 318 mm water. Because the average cumulative irrigation was only 265 mm during the fruit bearing period when ETc was relatively low for this early-ripening variety, the 680 mm water saved would correspond to 117% savings over the 583 mm seasonal average total water application.

### 3.3. Fruit yield and quality

The total number of peaches per tree showed no difference, at $P$ = 0.05 using the Tukey's studentized range (HSD) test, between the deficit irrigation (F2 and S2) and the 100% ETc irrigation treatments (F1 and S1) in both the 2007–2008 and the 2008–2009 growing seasons (Table 2). Fruit weight per tree in the S2 treatment was found smaller than other treatments in 2007–2008, but the difference was not significant in the 2008–2009 season. The weight per fruit in the S2 treatment was also found to be smaller than the 100% ETc treatments in the 2007–2008 season. In 2008–2009,

**Table 1**
Total irrigation water applied in the 2007–2008 and 2008–2009 growing seasons of an early-ripening peach at Parlier, CA.

| Treatment[a] | Cumulative irrigation (mm) | | | |
|---|---|---|---|---|
| | June–November 2007 Non-fruit bearing | March–May 2008 Fruit bearing | June–November 2008 Non-fruit bearing | March–May 2009 Fruit bearing |
| F1 | 1030 | 292 | 1111 | 267 |
| F2 | 405 | 297 | 366 | 260 |
| S1 | 977 | 267 | 870 | 221 |
| S2 | 241 | 275 | 259 | 231 |

[a] Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.

**Table 2**
Peach yield and yield parameters in the 2007–2008 and 2008–2009 growing season responding to different irrigation treatments at Parlier, CA.

| Treatment[a] | Yield parameters[b] | | | | | |
|---|---|---|---|---|---|---|
| | 2007–2008 Season | | | 2008–2009 Season | | |
| | No. of fruit per tree (–) | Fruit weight per tree (kg) | Weight per fruit (kg) | No. of fruit per tree (–) | Fruit weight per tree (kg) | Weight per fruit (kg) |
| F1 | 178a* | 21.9a* | 0.123a | 97a | 12.2a | 0.128a |
| F2 | 183a* | 22.2a* | 0.121ab | 94a | 11.3a | 0.120bc |
| S1 | 174a* | 21.2a* | 0.124a | 85a | 10.9a | 0.126ab |
| S2 | 160a* | 18.3b* | 0.115b | 82a | 9.6a | 0.118c |

[a] Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.
[b] Means followed by a different letter (within a column) are significantly different at $P = 0.05$ according to the Tukey's studentized range (HSD) test.
* Significantly different from the 2008–2009 season at $P = 0.01$ by two-tailed Student's *t*-test.

**Table 3**
Peach fruit quality parameters from the 2007–2008 growing season responding to different irrigation treatments at Parlier, CA.

| Treatment[a] | Fruit quality parameters[b] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Double (%) | Deep suture (%) | External split (%) | Dimple (%) | Deformed (%) | Split pit (%) | Marketable fruit (%) |
| F1 | 0.66a | 27.4a | 1.09a | 2.21a | 14.5ab | 2.94a | 54a |
| F2 | 0.91a | 30.5a | 0.80a | 2.31a | 19.4ab | 2.43a | 46bc |
| S1 | 0.55a | 32.2a | 0.94a | 1.88a | 12.1a | 1.38a | 52ab |
| S2 | 2.87b | 31.4a | 1.16a | 1.17a | 20.1b | 1.38a | 43c |

[a] Irrigation treatment F1 = furrow irrigation to replace 100% crop evapotranspiration (ETc); F2, furrow irrigation initiated when stem water potential reached −2 MPa; S1, subsurface drip irrigation to replace 100% ETc; S2, subsurface drip irrigation to replace 25% ETc.
[b] Means followed by a different letter (within a column) are significantly different at $P = 0.05$ according to the Tukey's studentized range (HSD) test.

the weight per fruit was smaller in the deficit irrigation treatments (F2, S2) than the respective 100% ETc irrigation treatments, e.g., F1 and S1, respectively. These results indicate that deficit irrigation with furrow application triggered at −2 MPa stem water potential did not cause yield losses (weight per area basis). Compared to the 2007–2008 season, statistical tests showed reduced fruit numbers and weight per tree in 2008–2009, but no difference in weight per fruit (Table 2). The lack of treatment effect was likely attributed to the non-severity of water stress from these deficit treatments. In a water stress study by Johnson et al. (1994), a reduction of 600 mm water application caused plum trees to defoliate, shoot and scaffold die back, and reduced yield in the following season. The timing of deficit treatment also could have different degrees of impact on stress response in Prunus tree species (Intrigliolo and Castel, 2004). Deficit irrigation by subsurface drip at 25% ETc significantly reduced yield for one year but not the second year (although numerically smaller). This effect might be attributed to the reduced wetting in the root zone when water was delivered via point-source emitters compared to furrows that would behave like a continuous line source of water at the soil surface. The other likely contributing factor was that the total amount of water applied in S2 was less than F2 in both seasons (Table 1). Despite improved application efficacy with the subsurface drip, the soil water profile at the end of each year showed lower values in the S2 than in the F2 treatments, especially for deeper soil depths (Fig. 8).

Consistent with findings reported in Johnson et al. (1992), postharvest deficit irrigation in the S2 treatment showed significantly higher numbers of fruit doubles or lower marketable fruits (Table 3). Other fruit quality parameters did not appear to be significantly impacted by the postharvest deficit irrigation treatments.

## 4. Conclusions and future directions

Infrared canopy temperature measurements provided a clear assessment of plant water stress in this early-ripening peach when subjected to postharvest deficit irrigation schemes. As indicated in Naor (2008), the temperature-based approaches, including thermal imaging, were promising methods for assessing crop water stresses, especially in the high radiative arid or semi-arid climates such as in the San Joaquin Valley of California. The results presented in this study were mostly direct and indirect observations of soil and plant responses to the imposed treatment effects. Simple correlations between the infrared canopy temperature to air temperature difference or $\Delta T$ with stem water potential (Fig. 7) were useful for providing a guidance on water stress assessment for managing regulated deficit irrigation, at least on a relative scale. The simple relationships may also be used for assessing irrigation uniformity if differential water application is the primary cause for stresses (other than insects, diseases, or nutrient deficiency). The next phase is to develop a theoretically based mechanism of using the canopy temperature for irrigation scheduling in peach trees for either non-water-stressed (100% ETc replacement) or water-stressed deficit irrigation regimes. To achieve this goal, the first step is to determine a theoretical base for choosing the threshold $\Delta T$ to trigger the onset of an irrigation event. Correlations with stem water potential, such as that in Fig. 7, may be used to find the threshold $\Delta T$, but correction for non-linear stomatal responses at high vapor pressure deficit conditions (Glenn et al., 1989), such as in the San Joaquin Valley of California, should be considered. An energy balance-based approach for finding the non-water-stressed baseline, such as that proposed in Alves and Pereira (2000), may likely be reconfigured for tree crops such as peaches to find the estimation of threshold $\Delta T$. The task of determining how much water to apply using primarily the $\Delta T$ data is more challenging because relating $\Delta T$ to cumulative latent heat likely has more uncertainties involved than finding the threshold $\Delta T$ to trigger irrigation. One possible method is to use the cumulative time exceeding the threshold $\Delta T$ as demonstrated for cotton (Wanjura and Upchurch, 1997). Additional theoretical development and field experimentation are needed.

## Acknowledgements

We thank Matthew Gonzales and Octavio Viveros for overall assistance on installing the infrared temperature sensors, carrying out the irrigation treatments, and making the soil water content and stem water potential measurements. The authors also acknowledge help from Nancy Goodell and Curtis Koga on yield and quality assessment during peach harvest.

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